HIGHER MODES IN COAXIAL RF LINES

H. NEUBAUER and F. R. HUBER
Rohde & Schwarz
Munchen, Germany

INTRODUCTION

Coaxial RF lines should be excited with waves that are free from longitudinal components, i.e., coaxial or TEM mode. As in the case of hollow waveguides, however, many different modes may occur in coaxial lines besides the fundamental. In both cases it is customary to prevent or suppress higher wave modes.

In contrast to a true hollow waveguide, a coaxial line is always inhomogeneous and, with its dielectric inner conductor beads, favours the occurrence of higher resonances; this does not apply to constructions using a solid dielectric or to quasi-homogeneous lines such as those using a helical dielectric. A study of guided waves in coaxial lines is thus mainly concerned with dielectric beads. Until recently, these problems had only been touched on by a few authors, with the exception of G. Spinner, who wrote a detailed dissertation[1] on insulating beads in coaxial lines and their resonance phenomena.

Only in recent years did this subject win topical interest, in fact from two different sides at the same time.

Firstly, in the middle of the 1960's, the power transmitted by UHF TV transmitters increased tremendously as a result of the network planning carried out for TV services and made possible by the development of efficient decimetre tetrodes and klystrons. Effective powers of 50 kW at MHz are now nothing out of the ordinary. At this frequency, the guided wave mode H_{11} (TE_{11}) can occur in a coaxial line (50 Ω) whose outer conductor has an inner diameter of 169 mm, a quantity matched to the power mentioned above; the outer diameter of coaxial lines realized in practice must be much smaller on account of the unavoidable inner conductor beads. If coaxial lines are to be used at all for such purposes, the guided-wave effects must be accurately known and the inner conductor beads carefully dimensioned.

Secondly, during the last few years increased interest has been shown in coaxial impedance standards for very high frequencies. This can be attributed to the work of the Subcommittee on Precision Coaxial Connectors of the IEEE Technical Committee on High Frequency Measurements, which aims at using the coaxial types up to about 5% below the cutoff frequency of the discontinuity-free coaxial air line concerned.[2] Hollow waveguide effects occurring in some connectors that were recommended for standardization provided the reason for a closer study of guided-wave excitation in coaxial lines.

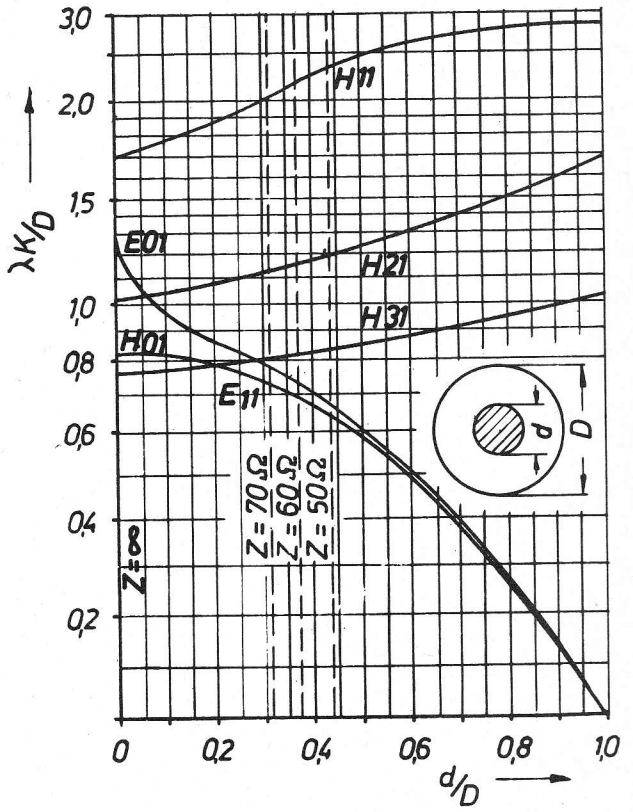

Fig. 1 — Cutoff wavelengths of the main types of guided waves in a coaxial air line.

HIGHER MODES IN HOMOGENEOUS COAXIAL LINES

In this paper, a homogeneous coaxial line should be understood as one in which the diameter of the outer and inner conductors does not change throughout. This is quite a considerable restriction, since in practice grooves of different depth must be provided for the bead supports on the inner and outer conductors, otherwise it would not be possible to obtain the same char-

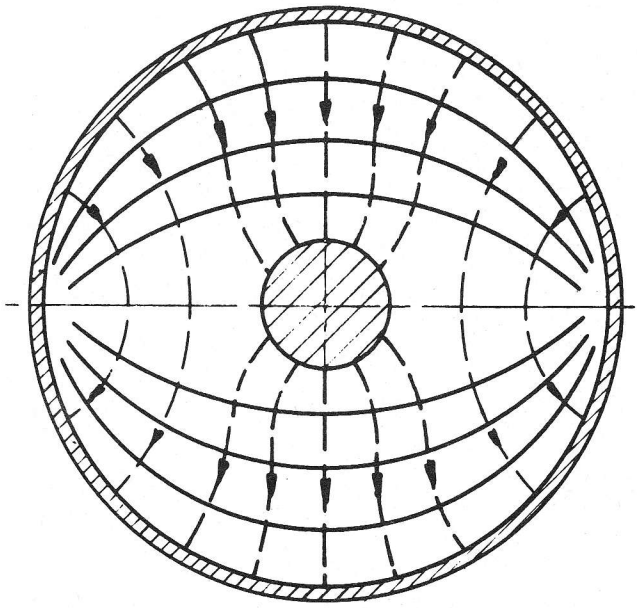

Fig. 2 — Field pattern of the H_{11} (TE_{11}) wave in the cross section of a coaxial line.
Solid: H lines;
Dashed: E lines.

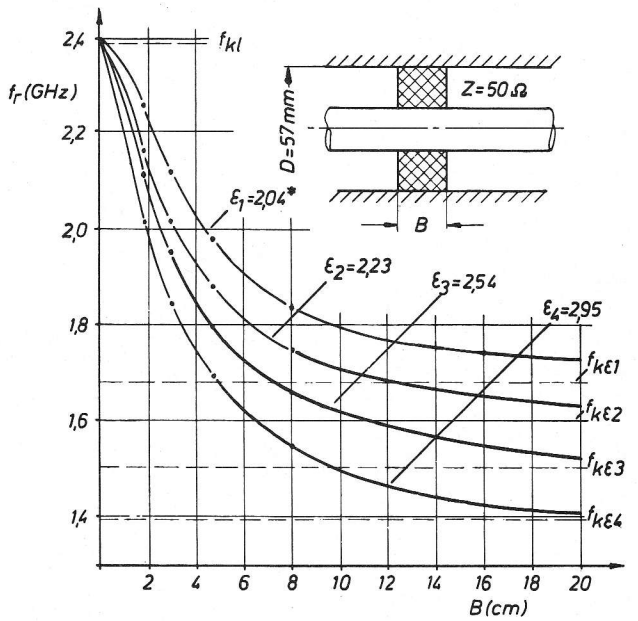

Fig. 3 — First resonance (H_{11}, TE_{11}) of a bead as a function of the bead width. Relative permittivity: parameter.
f_{kL} = critical frequency of air-filled coaxial line;
$f_{k\varepsilon}$ = critical frequency of dielectric-filled coaxial line;
*** curve for ε_1, transformed according to Ref. 4.**

acteristic impedance inside and outside the bead; discontinuities are thus obtained which affect the wave excitation. In theory, however, it is simpler to deal with a homogeneous coaxial line.

The cutoff wavelengths below which the particular modes occur are given in Fig. 1 for the principal modes as a function of the diameter ratio of the coaxial line.[3]

Figure 1 shows that the magnetic fundamental H_{11} (TE_{11}) occurs at a much greater wavelength (lower operating frequencies) than the higher modes and that the cutoff wavelength increases as the characteristic impedance of the line is reduced. A 50-Ω line is thus rather unsuitable from this point of view. When evaluating Fig. 1, it is important to note that the characteristic impedance only indirectly determines the cutoff wavelength of a hollow waveguide; with dielectric-filled lines ($\varepsilon_r > 1$), the characteristic impedance of the air line must first be determined with the aid of the diameter ratio, and the cutoff wavelength in the air from Fig. 1. The actual cutoff wavelength is obtained by multiplying the result by $\sqrt{\varepsilon_r}$.

The electric field pattern of the H_{11} (TE_{11}) wave in the cross section of the coaxial line is represented in Fig. 2.[3] Figure 2 also shows why the cutoff frequency drops with a low characteristic impedance: the inner conductor attracts electric flux lines and thus acts as a capacitive load on the resonant cavities assumed to be on the right and left of the inner conductor. This effect is identical with that intentionally caused in ridge waveguides, which also leads to a reduction of the critical frequency. The following relation is true of the H_{11} (TE_{11}) wave according to[3]

$$\lambda_k \approx \frac{\pi}{2}(D + d),$$

where d and D represent the outer diameter of the inner conductor and the inner diameter of the outer conductor respectively.

(λ_k = critical wavelength)

λ_k thus roughly corresponds to the average circumference of the line. Here again it can be seen that the cutoff wavelength grows with decreasing characteristic impedance, that is, the cutoff frequency is reduced.

As already mentioned, dielectric-filled coaxial lines ($\varepsilon_r > 1$) have a lower cutoff frequency than air-filled lines. This is even more complicated in practice since the beads are of finite length, so that a combined air-filled and dielectric-filled coaxial line is obtained. Bussey and Beatty present a theory for mode excitation in a bead of finite length within a homogeneous coaxial line.[4] This report also deals with a system of two adjacent beads, which is of great practical importance, and gives measured values for single beads and pairs of beads.

The authors of the present article have studied homogeneous and inhomogeneous coaxial lines in some detail and not only confirm the test results found by Bussey and Beatty, but are also able to present additional values.

The resonant frequencies of beads in a homogeneous coaxial line are shown as a function of the bead width in Fig. 3; the relative permittivity of the bead material is given as a parameter. A characteristic impedance of 50 Ω and an inner diameter of the outer conductor of 57 mm are assumed. This inner diameter was also used for all subsequent test series yet to be described. It is quite possible to use these curves for other diameters, applying the well-known model law (wavelength proportional to linear dimension).

All the main features of bead resonances can be seen in Fig. 3. The first point of interest is that there are no exceptional bead dimensions. This shows it is wrong to assume that a particular relation must exist between

the bead width and the wavelength to permit resonance. On the contrary, all beads can achieve resonance provided they fulfill the condition

$$\infty > B > 0$$

where B = the bead width. The resonant frequency obtained when B approaches ∞, that is, for a homogeneous, dielectric-filled line, results from the fact that the phase velocity within the dielectric must also tend towards infinity to permit resonance.

The resonant frequency obtained with B approaching 0 is of greater interest, since it is determined by the cutoff frequency of the coaxial air line. Beyond this limit, wave propagation in the coaxial air line is regular instead of aperiodic. It is, however, essential for the resonance mechanism of the bead that the wave propagation in an axial direction in the zones outside the bead is only finite, that is, aperiodic. Since there is no regular propagation, the electromagnetic energy flowing back and forth in the bead is reflected without loss from the faces of the bead as though they had a metal coating of infinite conductivity. The usual arrangement is, however, somewhat different in that reactances connected at the ends of the bead are formed from air line sections in which only aperiodic propagation is possible. These reactances interact with the space inside the bead such that resonances occur as shown in Fig. 3.

Since resonance is not only determined by the field inside a bead but is also considerably influenced by the space outside, it is an obvious conclusion that a second bead in the vicinity of the first one will affect the resonance conditions. This is demonstrated in Fig. 4 for two different dielectric constants. Figure 4 also shows that with finite spacing of the two beads, two resonances are obtained, the higher of which is of no practical significance. Since both beads are symmetrical, it may be assumed that they achieve resonance at the same time. If non-symmetrical beads were used, a double curve would probably be obtained. It is important to note that the distance A (distance between the two beads) must achieve the quite considerable value of about 2 D to minimize interaction of the beads. When applied to coaxial connectors, this means that a supporting disc must be about 1.0 D away from the contact plane, e.g., about 7 mm for a 7-mm connector.

Figure 5 shows very clearly how the resonance field extends into the air space. Even with a large width (B = 74 mm) an excessively high field still exists. The fact that the expansion of the resonance field, or rather the interference of the voltage distribution is greatest with the thinnest bead is corroborated in Fig. 3. Here, a thin bead is used and the state of regular propagation is almost achieved in the coaxial air line, so the field, which is still aperiodic, occupies an exceptionally large space.

In many cases of practical relevance, undisturbed propagation of an aperiodic field cannot be achieved. A typical example of this phenomena is found when a change in the diameter of the coaxial line occurs near the bead. An extreme case would be when changes in diameter occur immediately before and after the bead; this would give rise to an ideal, metal-enclosed cavity resonator since the field slightly penetrating into the narrower coaxial line sections is negligible, provided that the ratio of the two line diameters is sufficiently large. The resonant frequency of such a resonator can be derived from the well-known formula stating the

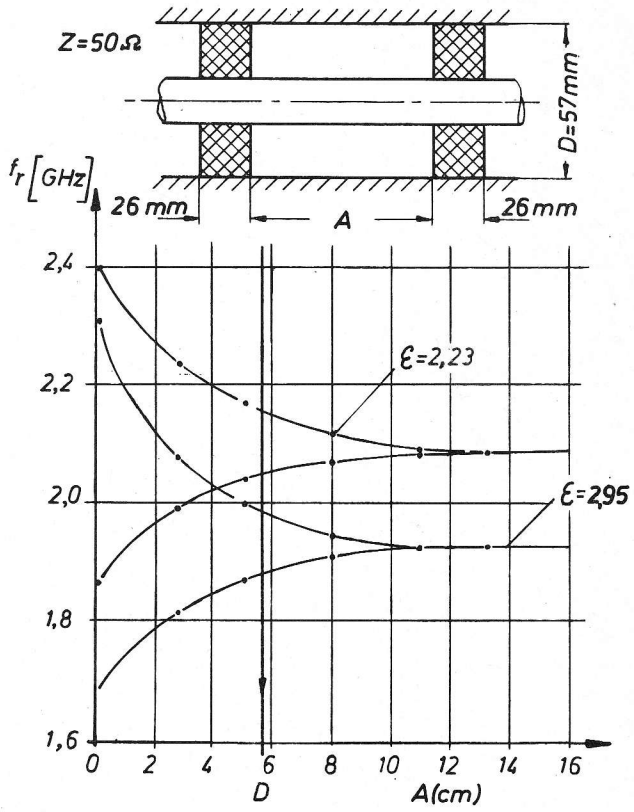

Fig. 4 — Resonance frequency of two beads as a function of the distance A.

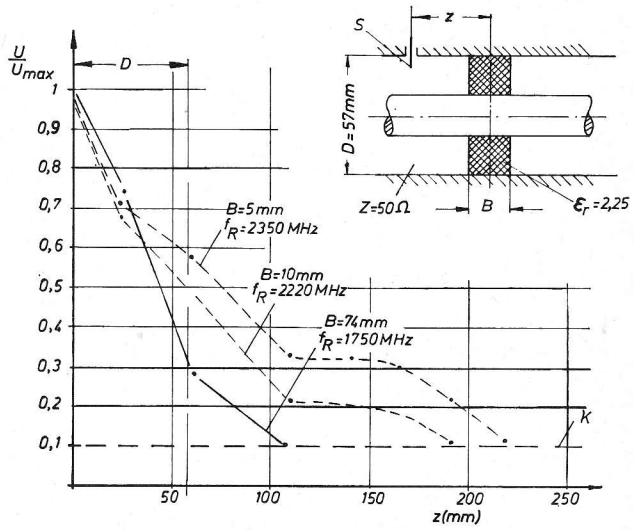

Fig. 5 — Relative voltage distribution along a coaxial line with a bead as an H_{11} (TE_{11}) resonator; parameter: bead width.
K = approximate level of wave in coaxial line without discontinuity;
S = test probe (can be moved in steps).

relation between the wavelength in the hollow waveguide, the critical wavelength in the waveguide and the wavelength in the air:

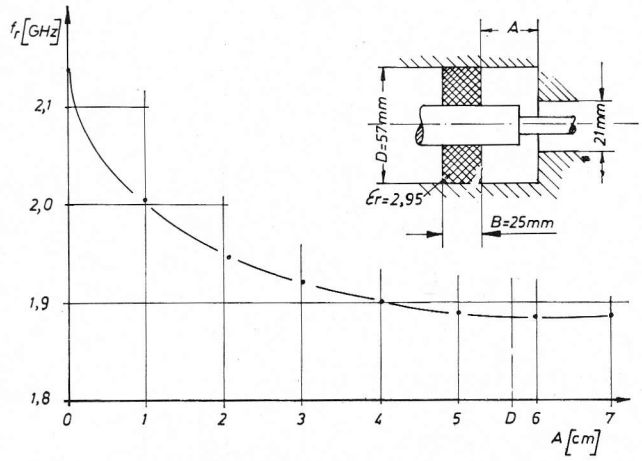

Fig. 6 — Resonance frequency of a bead with a change in cross section on one side, as a function of the distance A between the bead and the change in cross section.

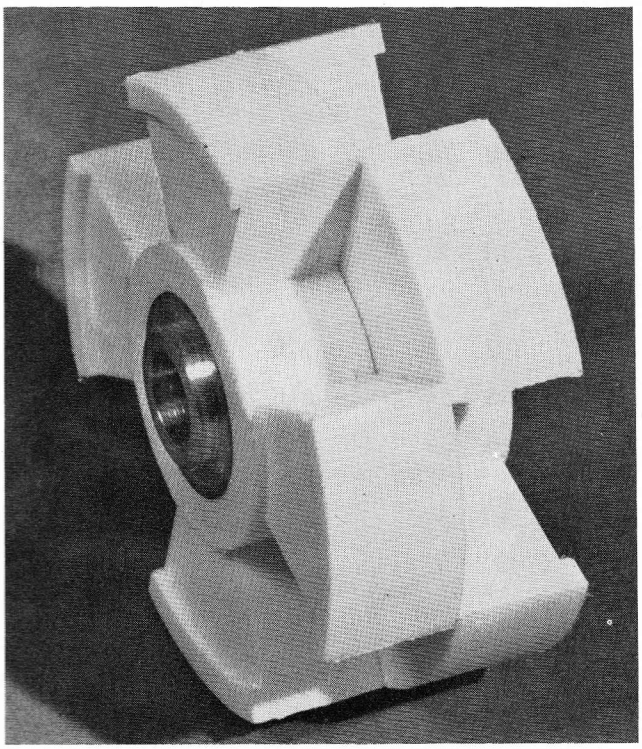

Fig. 7 — Star bead of Precifix connector.

$$\lambda_o = \frac{\lambda_H}{\sqrt{1 + \left(\frac{\lambda_H}{\lambda_K}\right)^2}}$$

λ_o = wavelength in the air

λ_H = wavelength in hollow waveguide (coaxial line)

λ_K = critical wavelength in hollow waveguide (coaxial line).

For the first resonance, H_{11} (TE_{11}), the width B of a metal-enclosed bead of dielectric material (ε_r) must fulfill the following condition:

$$B = \lambda_H/2 \times \sqrt{\varepsilon_R}.$$

By substituting this relation in the last but one equation, the resonance wavelength in the air (λ_{oR}) is then

$$\lambda_{oR} = \frac{2B\sqrt{\varepsilon_r}}{1 + \left(\frac{2B\sqrt{\varepsilon_r}}{\lambda_k}\right)^2}$$

If the changes in diameter are not next to the bead, so that a space occurs in which the aperiodic field is accommodated, the resonant frequency is bound to drop since the resonator is now loaded reactively on both sides. A case of great practical importance is when a coaxial line has a change in diameter only on one side; this effect is illustrated in Fig. 6. The first resonance occurs at 1.91 GHz when the coaxial line on each side of the bead is without discontinuities (B = 25 mm, $\varepsilon_r = 2.95$) according to Figs. 3 and 4 ($A = \infty$); however, the resonant frequency rises to 2.14 GHz according to Fig. 6 (A = O) when the bead is limited by a change in diameter on one side. As A increases, the resonant frequency decreases, as is to be expected since the space available for the aperiodic field becomes constantly larger. It is interesting to note that no dependence is shown from about A = 57 mm (A = D). This is also implied in Fig. 4, where from A = 2D onwards (a free space of length D is available for each bead) there is no longer any great influence and from 3D onwards the influence is negligible. By substitution of the actual B and ε_r values in the foregoing formula for λ_{oR} a wavelength λ_{oR} of 80 mm is obtained, which corresponds to a resonant frequency of 3.75 GHz. This shows that the resonant frequency of a bead is not much affected when a change in diameter occurs on one side of the bead (from 1.91 GHz to 2.15 GHz); on the other hand, a second change in diameter will cause quite a considerable resonant frequency shift (from 2.15 GHz to 3.75 GHz).

RELATIVE PERMITTIVITY

A supporting bead with a relative permittivity of more than unity narrows the frequency range of a coaxial line as the permittivity rises. This bars the use of all RF insulating materials of high dielectric constant, including ceramic-based insulators, if the line is operated near its cutoff frequency and special bead designs are not used. Unfortunately, no RF insulating material with a permittivity of less than 2 has yet been found; the line characteristics are thus always affected.

It is quite conceivable that a mixed dielectric could improve the situation. A combination with air would seem to be the most obvious solution. Foamed dielectrics, such as foamed polystyrene, would come very close to the desired value of unity but have proved unsuitable in other respects. They have the drawbacks of poor homogeneity, insufficient reproducibility in batch production and generally insufficient mechanical strength. The method of providing a circle of axial holes in solid beads is not very effective since only a small amount of dielectric material is then removed.

A high dielectric constant of the bead material affects not only the susceptibility of a coaxial line to waveguide resonances but also other characteristics:

Large field distortions cause parts of the wave to be reflected, and these reflections cannot be compensated for.

To obtain equal characteristic impedances inside and outside the bead — a necessity for low reflection — the inner and outer conductors must be correspondingly overcut; this means that the transmissible power is limited and the susceptibility to waveguide effects increased.

It is, therefore, only possible to produce suitable coaxial lines and connectors if the dielectric constant can be kept low. A highly satisfactory design was found in 1962: the star-shaped bead.[5] The bead is basically the same as the original cylindrical type but sector-shaped parts of the bead material have been removed almost up to the inner conductor. Since with this construction most of the electric flux lines run parallel to the bead material or cut through it at right angles, it was possible to derive a formula for finding the characteristic impedance of this bead[5]:

$$Z = 60 \sqrt{\frac{\varepsilon_r \times \frac{1}{\ln \frac{d_2}{d_1}} + \frac{\Sigma\alpha}{2\pi}(\varepsilon_r - 1) + 1 \frac{1}{\ln \frac{d_3}{d_2}} \ln \frac{d_3}{d_1}}{\varepsilon_r \times \frac{1}{\ln \frac{d_2}{d_1}} \quad \frac{\Sigma d}{2\pi}(\varepsilon_r - 1) + 1 \frac{1}{\ln \frac{d_3}{d_2}}}}$$

d_1 = outer diameter of inner conductor

d_2 = outer diameter of centre ring of the bead

d_3 = inner conductor diameter of outer conductor

Σd = angle sum of the individual bead sectors.

Other authors now also working on this field have arrived at the same results.[6,7]

A typical star bead is shown in Fig. 7; here, two identical bead halves are turned against each other by half a division to avoid the penetration of foreign matter into the inside of the coaxial line or connectors. Beads of this kind are used in the 7-mm precision connectors Dezifix A, Precifix A and Precifix AA* (see Fig. 8), and ensure a cutoff frequency of 18 GHz which could not otherwise be realized. More details can be found in the articles[8,9].

With the star construction shown in Fig. 7 a mean dielectric constant of 1.74 is obtained instead of 2.23 as with a solid bead (polypropylene). If very narrow gaps are left in between the spokes, the dielectric constant can be reduced so much that it would even be possible to use ceramic materials (Fig. 9).

The effect of the star shape (material: polypropylene; mean dielectric constant: 1.74) as compared with a conventional cylindrical bead (material: polyvinal carbazole; dielectric constant: 2.95) is shown in the following table, which refers to a 50-Ω coaxial line with an outer conductor inner diameter of 57 mm and an overcut of 63 mm near the bead.

* *The standard specifications of the IEEE Subcommittee on Precision Coaxial Connectors provide for two kinds of coupling mechanism for 7-mm connectors in the section "Precision Coaxial Connector Coupling Mechanisms, Contact Designs, and Higher Mode Resonances." Precifix A has a coupling mechanism according to Fig. 3 in this section and Precifix AA according to Fig. 5. The coupling mechanisms of both connectors can be exchanged.*

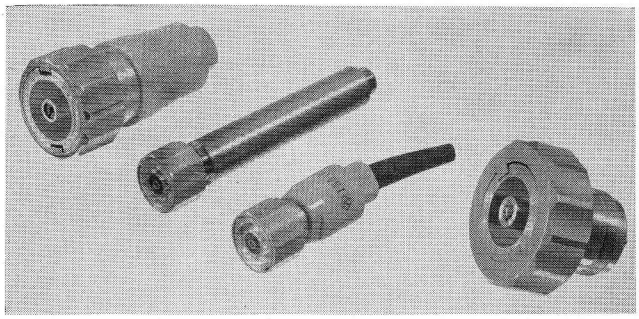

Fig. 8 — 7-mm R&S connectors Dezifix A and Precifix A.

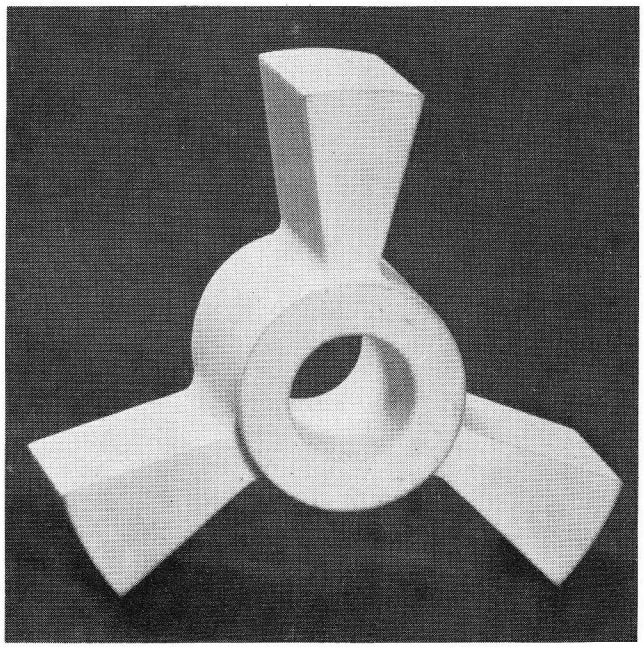

Fig. 9 — Star bead of ceramic material.

Cutoff frequencies of some coaxial configurations for th main wave modes:

Coaxial Configuration	$H_{11}=TE_{11}$	$H_{21}=TE_{21}$	$E_{01}=TM_{01}$
Homogeneous coaxial line without bead	2.38 GHz	4.66 GHz	9.24 GHz
Star bead $\epsilon_r = 1.74$	1.775 GHz	3.38 GHz	5.3 GHz
Solid bead $\epsilon_r = 2.95$	1.46 GHz	2.67 GHz	3.6 GHz

This table also shows that even with relatively large dielectric constants, the even higher modes only occur above the H_{11} (TE_{11}) cutoff frequency of a homogeneous coaxial line. Therefore, apart from solid beads with extremely high dielectric constants, it is quite permissible to concentrate the present study on the fundamental wave.

RESONANCE CHARACTERISTICS OF PRACTICAL BEADS WITH SPECIAL REFERENCE TO THE STAR BEAD

To avoid confusion, the section "Higher Modes in Homogeneous Coaxial Lines" dealt with cylindrical beads without overcut on the inner or outer conductor.

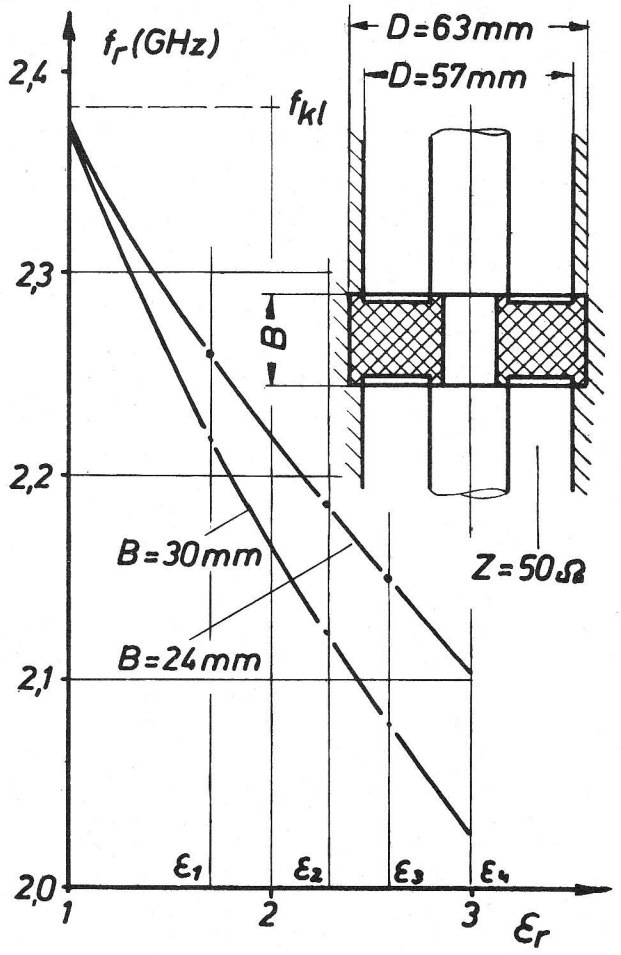

Fig. 10 — Relation between relative permittivity and H_{11} (TE_{11}) resonant frequency for compensated supporting beads.

f_{kl} = critical frequency of coaxial line without discontinuity;
ε_1 = 1.74: star bead of polypropylene;
ε_2 = 2.23: cylindrical bead of polypropylene;
ε_3 = 2.54: cylindrical bead of polystyrene;
ε_4 = 2.95: cylindrical bead of polyvinyl carbazole.

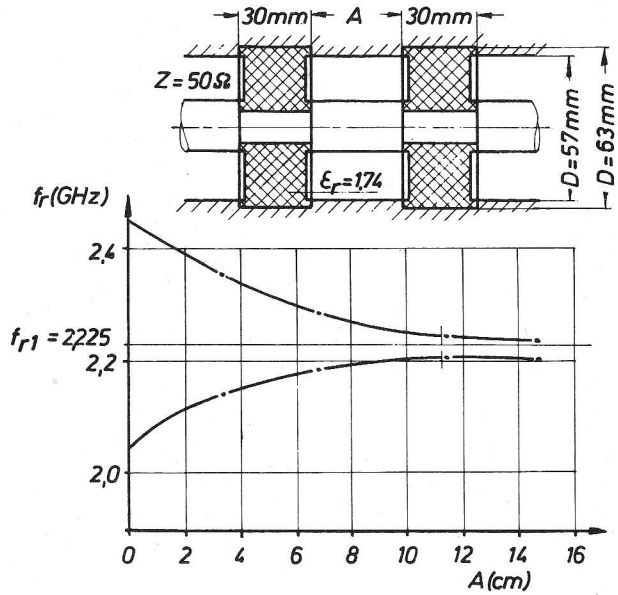

Fig. 11 — Resonant frequency of two star beads as a function of the distance A.
f_{r1} = resonant frequency of a bead.

Constructions of this kind are not suitable for practical purposes because of their reflection coefficient. To obtain reflection characteristics meeting the latest technical requirements extra compensation is required on the circular faces of the beads in addition to the overcutting already mentioned. This is usually realized by means of circular grooves and is required both for solid beads and beads made of inhomogeneous dielectric, e.g., perforated or star beads. The resonance characteristics of such beads are so complicated as to make theoretical calculation impossible. For this reason series of tests were carried out to determine some of the most essential characteristics for practical purposes. Here again, a 57-mm coaxial line was used for the experiments; as already mentioned, other coaxial dimensions may be readily substituted by applying the model law.

Figure 10 shows the relation between the H_{11} (TE_{11}) resonant frequencies of compensated beads 24 and 30 mm in width, and the relative permittivities.

Analogously with Fig. 4, Fig. 11 shows the interaction of compensated beads overcut at the inner and outer conductors. It is worth noting that owing to the lower mean dielectric constant, the resonant frequency is much higher than shown in the examples of Fig. 4, despite the altogether more unfavourable conditions, i.e., large bead width and large free space due to overcuts in the inner and outer conductors. Here again, it becomes apparent that the clear distance between beads must be about 120 mm to minimize interaction. As already indicated, the connector designer must therefore ensure that the interface distance between the inner conductor beads is at least twice the diameter of the coaxial line; the dimensions of the 7-mm Dezifix A and Precifix A (AA) connectors shown in Fig. 8 meet this requirement with a clear distance of 14 mm between beads.

RESONANCE EXCITATION

The Technical Subcommittee on Precision Coaxial Connectors of the IEEE Group Instrumentation and Measurements first specified cutoff frequencies of 18 GHz for 7-mm precision connectors and 9 GHz for 14-mm versions. The discovery that these values do not hold for connectors with solid cylindrical beads was made rather late, but the specification was then accordingly changed, at least temporarily. The reason why this point had been overlooked for such a long time despite thorough tests on the connectors can be found in the fact that resonance phenomena occur in extremely narrow bands because of the very high Q of the resonating bodies (typical values: resonance bandwidth 20 kHz at 18 GHz, that is, approx. 1/1000). Such phenomena are the result of certain coincidences and thus difficult to reproduce. A number of papers prepared on this subject disclose interesting details.[10–13] An essential part of these investigations dealt with the excitation mechanism of the H_{11} (TE_{11}) wave. The problem first seemed even more puzzling since on the one hand the coaxial lines were strictly symmetrical, all the more so as precision requirements rose, but on the other hand it was known that an H_{11} (TE_{11}) wave can only be excited by asymmetry. Likely exciters of the field in a hollow waveguide are eccentricity of the inner and outer conductors, manufacturing tolerances that are not rotation-symmetrical (particularly of the bead), foreign

bodies and eccentric contact faults on the outer conductor (sometimes, but to a lesser extent, on the inner conductor also). The problem became even more difficult since in the first model tests it was only seldom possible to produce waveguide resonances. From comprehensive experiments now carried out it seems safe to assume that waveguide resonances in straight lines arise from contact faults particularly of the outer conductor. This does not necessarily clash with the fact that precision connectors are made to contact perfectly to ensure favourable leakage. It seems that even an extremely slight irregularity in the contact resistance along the perimeter of the outer conductor will suffice to disrupt the even distribution of the charge density, thus fulfilling the main condition for the occurrence of waveguide resonances. Obviously, the contact point of a coaxial connector is much more likely to cause this effect than a tight screw or soldered connection. This circumstance also underlines the importance of keeping a certain distance between the point of contact on the connector and the bead.

As already implied, special measures are required to excite resonances in a homogeneous coaxial line. The bead was examined with the aid of different-sized dielectric bodies shaped like the segment of a circle. A segment of maximum size completely filled out a section of a star support. The test item and test result are shown in Fig. 12. It can be seen that the intensity of resonance, expressed here by the additional reflection coefficient, always depends on the magnitude of the discontinuity, in this case the segment. A slight shift of the resonant frequency f_r is a side-effect of the change in the mean dielectric constant of the bead, following the insertion of the segment. As can be expected, the test showed that a bead is largely insensitive to mechanical tolerances. By inserting a segment with an α of 6°, an additional reflection coefficient of only 3% is caused; a discontinuity of this kind, however, corresponds to a quite considerable manufacturing tolerance which, with some care, can be easily avoided in practice.

In the test shown in Fig. 12, the segment was inserted directly into the bead. Figure 13, however, shows the effect of a segment of $\alpha = 43°$ which is further away from the bead. It is interesting to note that measurable resonance effects occur up to a distance of 3 D (D = diameter of coaxial line). This is a factor of great importance in the construction of coaxial configurations in which a bead capable of resonating is combined with an element distorting the field by radial asymmetrical effects (angle or tee piece).

It might be assumed that a resonating bead involves an appreciable additional attenuation due to internal losses. This would, however, be surprising since as already mentioned, the resonance bandwidth is extremely narrow, which is indicative of a high Q. In actual fact, power loss is mainly due to reflected energy (Fig. 14, curve 1). Only a low additional attenuation is caused by internal losses in the bead (difference approx. 0.3 dB between curves 2 and 3.)

These points are corroborated by Fig. 15, which shows sweep patterns of four 30-mm wide beads (the test results are also used in Fig. 10). The reflection coefficients shown in Fig. 15 can also be evaluated quantitively, since with excitation of constant intensity the

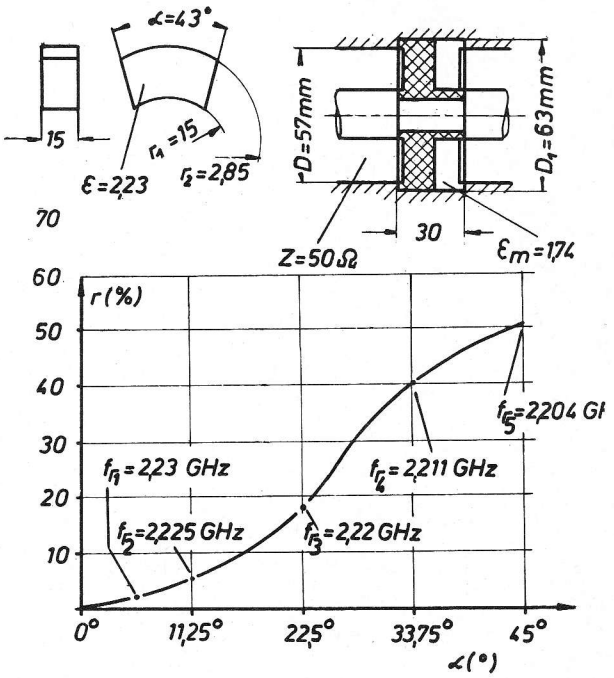

Fig. 12 — Reflection coefficient of a star bead as a function of the size of the discontinuity (see above drawing for definition of magnitude of discontinuity).
f_r = resonant frequency.

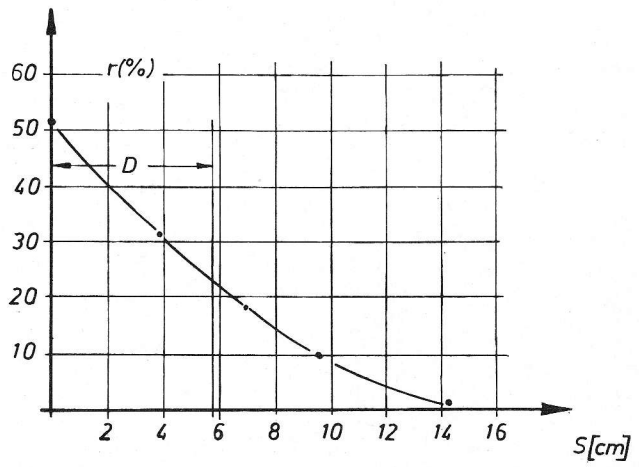

Fig. 13 — Reflection coefficient r of a star bead as a function of distance from discontinuity S.
S = distance between centre of discontinuity and centre of bead.
Magnitude of discontinuity uniformly 43° (see Fig. 12).

dissipation factor of the material is reflected in the amplitudes obtained. It is not surprising that the star-shaped bead exhibits a larger resonance amplitude since low losses are a typical feature of this type of bead — much of the material used in a cylindrical bead is replaced by air in the case of the star. It would, of course, be quite wrong to select a material whose dissipation factor is perhaps even higher than that of

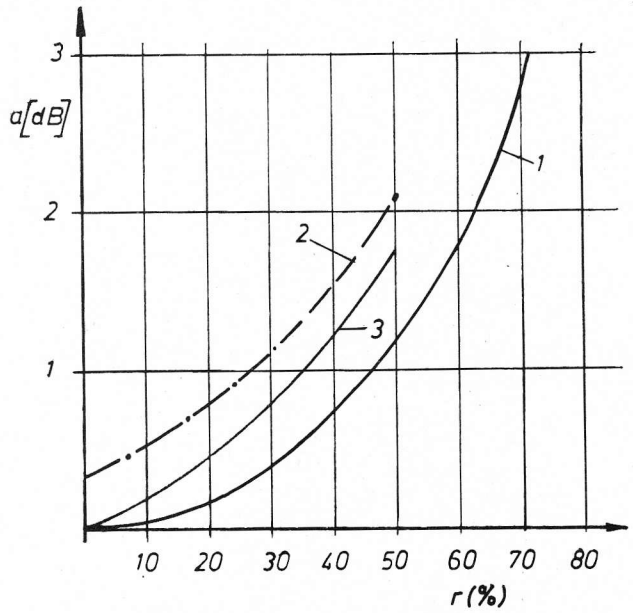

Fig. 14 — Effective attenuation as a function of reflection coefficient.
1) theoretical curve (power loss due to reflection coefficient);
2) values measured at bead resonance (star bead) including residual attenuation;
3) additional attenuation due to resonance effects.

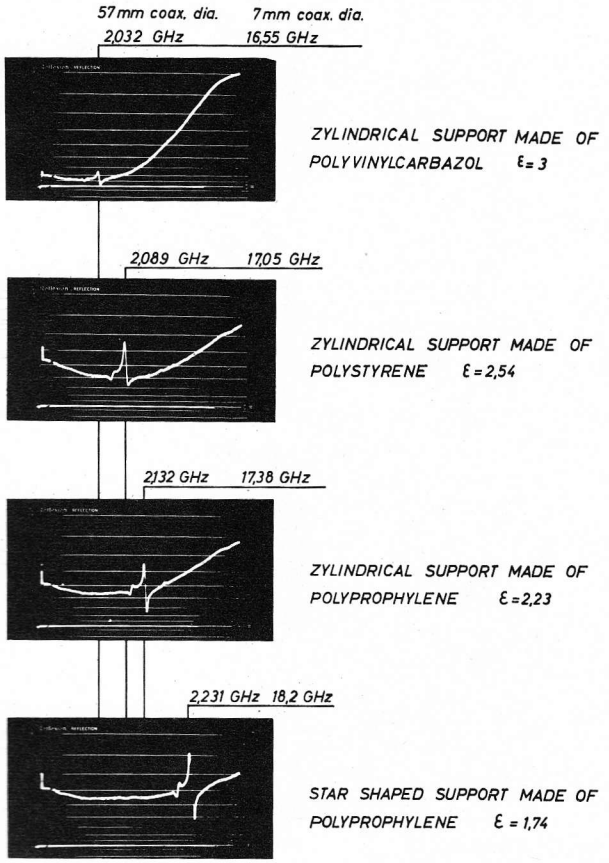

Fig. 15 — Reflection coefficient curves obtained for a 57-mm coaxial line by means of a sweep generator assembly and transformed for a 7-mm coaxial line, using the following beads:
Cylindrical bead of polyvinyl carbazole ($\varepsilon = 2.95 \approx 3$)
Cylindrical bead of polystyrene ($\varepsilon = 2.54$)
Cylindrical bead of polypropylene ($\varepsilon = 2.23$)
Star bead of polypropylene (mean $\varepsilon = 1.74$)

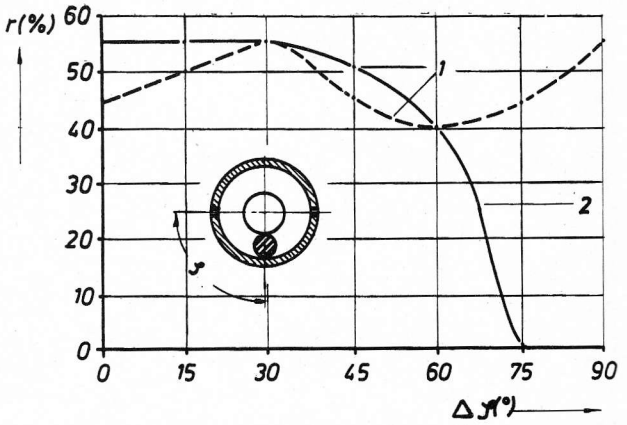

Fig. 16 — Resonance reflection coefficient of a compensated bead with a discontinuity and two longitudinal slots arranged 180° apart (80 mm long, 1 mm wide) on the outer conductor, as a function of the angle between the discontinuity and the plane of the slots.
1) with slots
2) without slots (for comparison).

polyvinyl carbazole (10^{-3}), since the total loss of connectors must be minimized in view of the power-handling capacity and the effective attenuation.

RESONANCE SUPPRESSION

The critical wavelength of the H_{11} (TE_{11}) resonance can be expressed according to[3] by the approximation formula:

$$\lambda_k \approx \frac{\pi}{2}(D + d).$$

The corresponding formula for the E_{01} (TM_{01}) wave, of little practical interest here, is $\lambda_k \approx D - d$. The first approximation formula shows that the critical wavelength roughly corresponds to the mean diameter of the space between the inner and outer conductors.

Further technical developments requiring greater powers at high frequencies may suggest the expediency of introducing "active" measures, such as resonance prohibiting elements, as well as the above-mentioned "passive" measures, i.e., avoiding discontinuities and above all reducing the mean dielectric constant of the bead material. The approximation formula for the cutoff wavelength H_{11} (TE_{11}) wave immediately shows that it is not advisable to embed a coaxial metal ring isolated from the inner and outer conductor into the bead material, since this would give rise to a ring-shaped space with a greater mean diameter. Experiments proved that such a measure leads to an increase in the critical wavelength, that is, to a reduction of the resonant frequency. It should, however, be possible to insert radial metal plates (isolated from the inner and/or outer conductor), which ought to stop the fundamental wave; however, this would considerably affect the characteristic impedance of the coaxial-line wave.

Since, like a ridge waveguide, the inner conductor of a coaxial line acts on the first guided wave as a

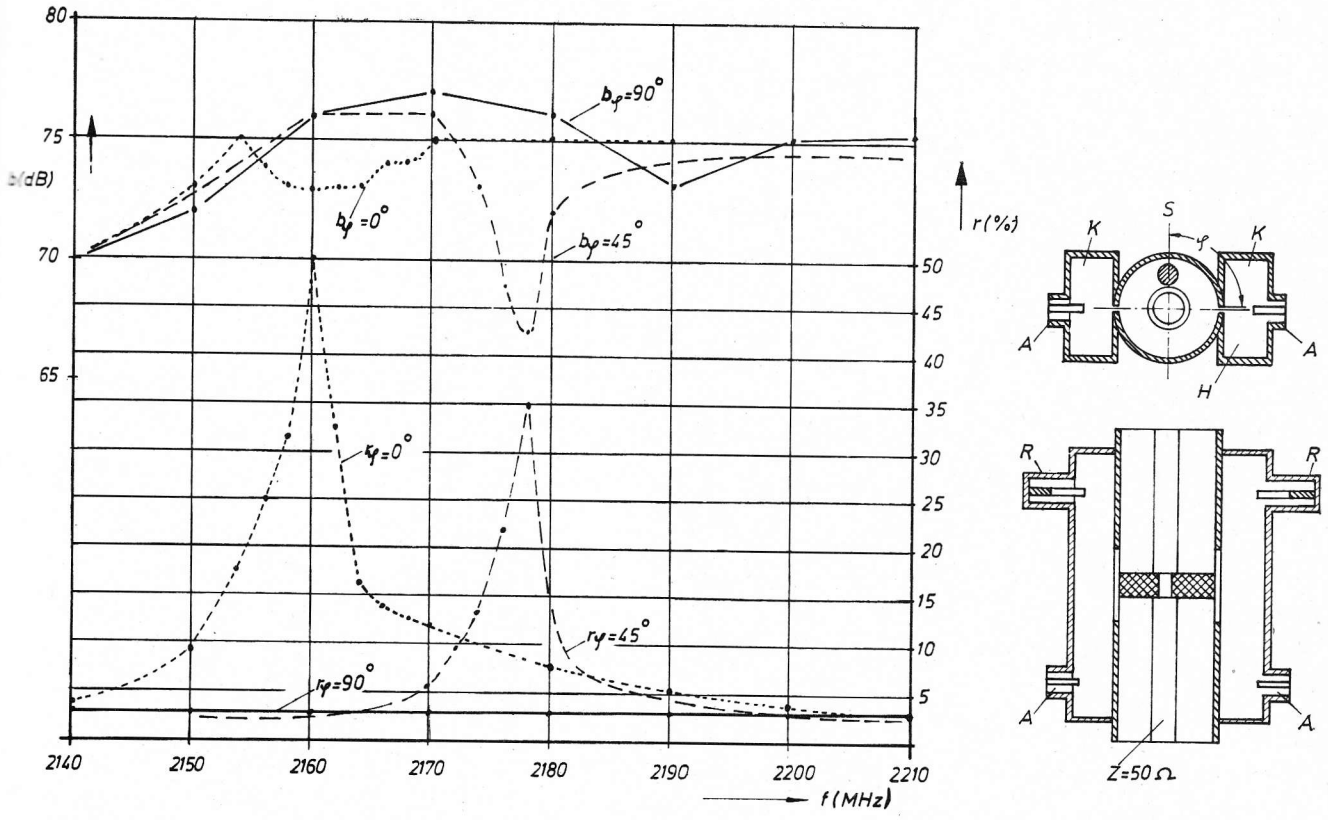

Fig. 17 — Reflection coefficient and power ratio between the interior of the line and the coupling cavities for a slotted coaxial line with a compensated bead. Inner diameter of outer conductor: 57 mm. Two opposite slots in the outer conductor; 80 mm long and 1 mm wide. Angle φ between plane of slots and discontinuity: parameter.

S = discontinuity
K = coupling cavities
R = terminating resistors
A = coupling out

shunt capacitance, the resonant frequency should be raised by isolating the inner conductor from the guided wave; the quantity d in the formula $\lambda_k \approx \frac{\pi}{2}(D + d)$ would then be reduced to zero. For thus purpose a longitudinal slot can be made in the tubular inner conductor, which will safely stop circular currents on the latter. This idea was tried out in a few experiments, but no unequivocal results were obtained.

Making a slot in the outer conductor did, however, prove very effective. Two slots made at an angle of 180° from each other on the outer conductor completely suppress the H_{11} (TE_{11}) resonance if the plane of each slot is at an angle of about 90° to the segment (Fig. 16).

Figure 17 supplies more exact information on the phenomena that occur at resonance of the bead. It gives as a function of frequency the reflection coefficient and, in another diagram, the relation between the power in the coaxial line and that coupled out into the coupling cavities, the angle between the segment and the slot plane being a parameter in each case. Here again, it can be seen that with $\varphi = 90°$ complete suppression of waveguide effects is achieved. An important point in this respect is that a large ratio exists between the power in the coaxial line and that in the coupling cavities. For this reason it will often be possible in practice to leave the slots uncovered and allow the "resonance power" to escape. On the other hand, no disadvantage is incurred by encapsulating the slots with metal covers and filling the inner space with an energy-absorbing medium to prevent secondary resonances. Even when 100 kW are transmitted in the coaxial line, only powers of the order of watts or less have to be transformed so that there is no danger of overheating.

Coaxial angle pieces (90°) cause considerable disruption in the field distribution. Nevertheless, no resonance could be detected below the cutoff frequency of a homogeneous coaxial line. On the other hand, even a well compensated angle piece will excite a dielectric bead to resonance if the bead is less than 3D (D = inner diameter of the outer conductor) away from the angle. An angle piece thus has a much stronger effect than a dielectric discontinuity (cf. Figs. 12 and 13). Figure 18 shows a test item demonstrating this point and the results obtained. With a closed outer conductor a noticeable bead resonance occurs (f_r = 2.234 GHz, r = 50%), which vanishes when four slots are made. A similar test in which the distance between angle and bead was increased to 164 mm, i.e., about 3D, still showed a distinct resonance with r = 15%.

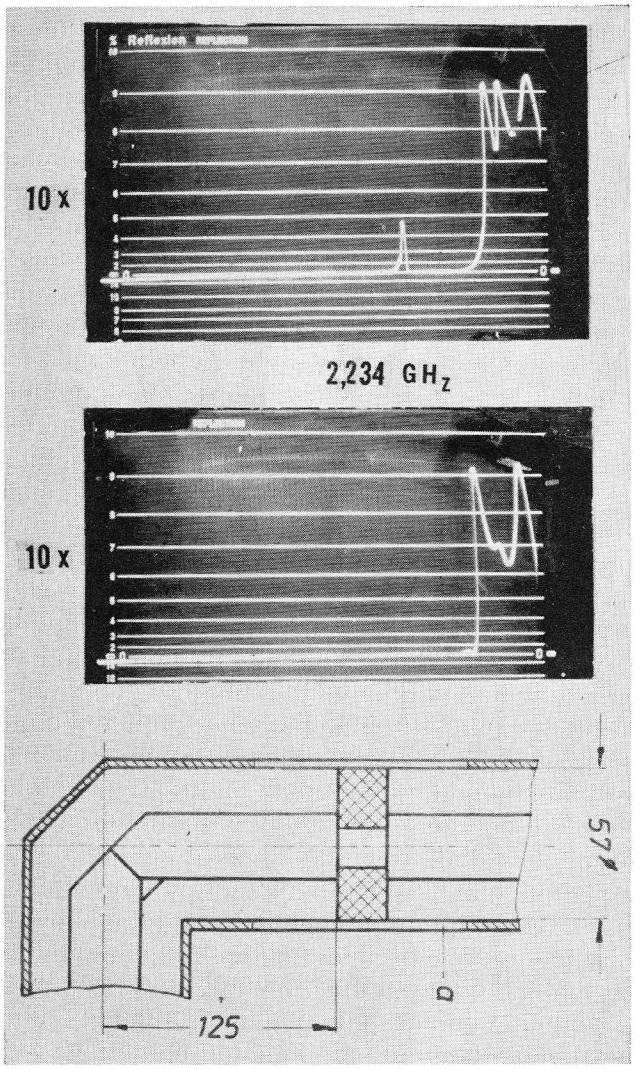

Fig. 18 — Angle piece with bead in a 57-mm line ($Z = 50\Omega$). Top: Closed outer conductor: strong resonance ($f_r = 2.234$ GHz, $r = 50\%$) Bottom: Four slots arranged at right angles (80 mm long, 1 mm wide): no resonance.

The fact that an angle piece causes a strong but well defined disturbance of the field makes it possible to use two instead of four slots. If they are to be fully effective, these two slots must be placed at an angle of 180° from each other in the same plane, which passes through the coaxial axis and is vertical to the plane of the angle piece; the slots must run in the same direction as the coaxial line.

These tests (see Figs. 12 and 13) also showed that the effect of a discontinuity is compensated by another discontinuity placed at an angle of 180° away; it is interesting to note that there is no difference whether the discontinuities are both on the same side or not. These discoveries allow a great many possibilities for compensating reproducible discontinuities which would lead to resonances. Beads with manufacturing tolerances can be tested for their susceptibility to resonances and "adjusted" by removing or adding a small amount of dielectric material; even discontinuity sources of a systematic nature, such as angle pieces, can be compensated for by means of suitably arranged dielectric or metal blocks. Of course, when using such methods, care must be taken not to affect the coaxial-line (TEM) wave. This is relatively simple since the coaxial-line (TEM) wave has a rotation-symmetrical electrical field and the H_{11} (TE_{11}) a directional one; a screw put through the outer conductor at a suitable spot and opposite to a correspondingly large hole or, more effectively, an overcut in the inner conductor, has a strong effect on the H_{11} (TE_{11}) wave but a negligible effect on the coaxial-line (TEM) wave.

CONCLUSION

This paper deals with guided-wave effects occurring near the cutoff frequency in coaxial lines. After mentioning the type and mechanism of these effects, practical examples are given with special reference to coaxial precision connectors. One section discusses the suppression of guided wave effects, distinguishing between passive measures (suitable design of conventional elements) and active measures (insertion of new elements). Coaxial angle pieces are dealt with as effective exciters of guided waves.

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